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Identifying Spring Barley Cultivars with Differential Response to Tillage

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Abstract: Cultivars and some cultivar mixtures of spring barley were grown under inversion and non-inversion tillage conditions for three or four years and assessed for disease and yield in order to obtain genotypes that can be used to determine the mechanisms of cultivation adaptation. In general, the higher-yielding cultivars under inversion tillage conditions gave lower yields under non-inversion tillage, whereas low-yielding older cultivars showed relatively smaller reductions in yield under non-inversion tillage. A few cultivars showed preferential yield performance for either inversion or non-inversion tillage and this was irrespective of their overall yield performance. There was no pedigree or breeding programme link between these cultivars and no above-ground gross morphological trait observed was associated with tillage adaptation. Root hairs may contribute to inversion tillage adaptation as a root hair absence mutant was associated with non-inversion adaptation and it is likely that other root-associated traits are responsible also for tillage adaptation. There was no overall cultivar or tillage interaction with rhynchosporium symptoms but a differential tillage interaction may occur in individual years. We have identified clearly contrasting cultivars and tested their across-season robustness with respect to tillage treatment for further detailed mechanistic studies and identification of tillage adaptation traits.

Keywords: spring barley; yield; disease; inversion tillage; non-inversion tillage

1. Introduction

Most cereal breeding programmes are carried out under inversion tillage and high input agronomy resulting in the selection of high yield and quality commercial varieties. This cultivar performance is realised in the field in practice when similar agronomic conditions are achieved. Independent cultivar evaluation schemes such as the UK's Agriculture and Horticulture Development Board (AHDB) Recommended List project are carried out under similar inversion tillage with high input agronomic regimes, although "untreated" yield is reported also for cereals where no fungicides are used but otherwise under the same agronomy. Organic growers have often asserted that cultivars selected under the above conditions may not be best suited to organic conditions and there is some evidence that adaptive traits suitable for organic conditions may be lost during this selection process. However, many elite cultivars selected by mainstream conventional breeders will have yield gains that do deliver under organic conditions [1]. The same argument could be made for non-inversion systems, in that selection under optimal conditions may not serve this growing tillage practice optimally.

There are several approaches to tillage described by terms such as ploughing, direct drilling, strip tillage, minimum tillage, no-till and zero-till, but arguably the biggest common factor is whether the soil structure is predominantly maintained at depth or disrupted. Particularly disruptive is ploughing which is designed to invert and disrupt the soil structure. Other tillage treatments have different degrees of disruption to varying depth but are normally shallower than ploughing and do not invert the soil profile. Several studies have shown significant interactions between cultivars and inversion/non-inversion tillage for wheat [2–4] changing cultivar rankings, although others showed no interaction [5–7]. In some other crops such as Soybean there was similarly no effect of cultivation on cultivar yield ranking [8], but no studies were found for spring barley.

There is an increasing trend towards the use of non-inversion tillage where upper soil horizons are disturbed to varying degrees but lower horizons remain undisturbed. For example, in England it is estimated that 46% of farms use some form of reduced tillage [9], while in other parts of the world such as Australia non-inversion tillage is almost universally practiced [10]. In European agriculture non-inversion/reduced tillage is most commonly in the form of minimum tillage where soil is disturbed at depths of, for example between 5 and 15 cm. However, strip tillage and direct drilling are approaches that cause even less disturbance, especially where discs are used rather than tines. Under such a gradient of reducing tillage, the physical, chemical and biological composition of the soil will increasingly differ from the ploughed and harrowed inversion tillage conditions typically used for breeding programmes. Therefore, whether cultivars selected in such breeding programmes are best suited to minimal disturbance non-inversion tillage practice on-farm should be questioned. In fact, it has been demonstrated that the quantitative trait loci associated with aspects of plant nutrition of a population of elite cereal genotypes is different in non-inversion tillage compared to conventional tillage, suggesting that different sets of traits are appropriate for the varying conditions [11]. Furthermore, as with organic agriculture, even if elite cultivars bred conventionally also show yield enhancement under non-inversion tillage, there may be additional beneficial traits for such conditions that are not being selected. Such trait-tillage associations would be indicated by differential response of cultivars to tillage treatments, i.e., a significant change in the cultivar yield rankings. Particular cultivars gain a reputation as being adapted to such agronomic conditions, but these are seldom validated in controlled trials.

No particular trait or set of traits have been shown to be associated with better yield under non-inversion tillage conditions in wheat but a mapping study using contrasting parents from Mexico and Australia and a study of historic Australian wheat cultivars implicated delayed senescence, rate of senescence once triggered, nitrogen uptake or use efficiency, early vigour and rooting traits as having some influence (e.g., [2,6]). As barley differs from wheat in these traits, and in the UK climate spring barley tends to be sink-limited whereas wheat tends be more variable between source and sink limitation [12–14] the effects of tillage on yield in particular may be very different from those of wheat. Therefore, the priority should be to determine whether there is an interaction of yield with soil tillage in barley that is not season-specific, and secondly to identify a suitable range of cultivars with contrasting yield response on which to focus subsequent detailed mechanistic studies.

The aim of this study was to (a) determine whether yield ranking changed between inversion and non-inversion tillage in spring barley and if so, to (b) identify a suitable range of cultivars with contrasting yield response to focus subsequent detailed mechanistic studies.

2. Materials and Methods

2.1. Cultivars

To test whether cultivars are differentially adapted to tillage conditions, we grew a range of spring barley cultivars, some no longer commercially available but present in the pedigrees of modern cultivars, some recent cultivars, some equal proportion mixtures or blends of four of the cultivars and some root hair mutants of one of these latter cultivars. Root hair traits are associated with adaptation to different soil strength and water content [15,16] and thus may indicate an adaptation mechanism if differentially adapted to tillage. The trial grown in each year had 34 entries and the same 34 were sown in three consecutive years (2013–2015) (Table 1). These were: Westminster (We), Waggon (Wa), Concerto (Co) and Optic (Op) as sometime widely-grown standard comparison cultivars; all six two-component equal proportion mixtures together with the 4-component equal proportion mixture (Op/Wa, Op/We, Op/Co, Wa/We, Wa/Co, We/Co and Op/We/Wa/Co); three root hair mutants of Optic (T-short root hairs-R, Q-no root hairs-S and V-short root hairs-R); and 20 other cultivars representing a diversity of origins and traits. In 2016, 11 new cultivars representing more recent AHDB Recommended List (RL) entries [17] were added, so 11 cultivars had to be removed to make space in the platform. These were selected either because they were the two-component mixtures (six entries) or appeared around the middle of the distribution of responses to tillage treatment in the 2013–2015 trials (Table 1). All cultivars were from conventional commercial breeding programs.

Table 1. Spring barley cultivars sown in Mid Pilmore soil cultivation trial.

Cultivar	Trials				Pedigree [a]/Note	Breeder
	2013	2014	2015	2016		
Optic (Op)	+	+	+	+	(Corniche*Force)*Chad	New Farm Crops Ltd. (Syngenta)
Westminster (We)	+	+	+	+	NSL 97-5547*Barke	Nickerson (UK) Ltd. (Limagrain)
Waggon (Wa)	+	+	+	+	NFC 499-69*Vortex	Syngenta Netherlands
Concerto (Co)	+	+	+	+	Minstrel*Westminster [c]	Limagrain
Op/Wa	+	+	+	-	(Equal component mixture)	Syngenta
Op/We	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Op/Co	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Wa/We	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Wa/Co	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
We/Co	+	+	+	-	(Equal component mixture)	Limagrain
Op/We/Wa/Co	+	+	+	+	(Equal component mixture)	Syngenta/Limagrain
T-short root hairs-R [c]	+	+	+	+	EMS mutant	-
Q-no root hairs-S [c]	+	+	+	+	EMS mutant	-
V-short root hairs-R [c]	+	+	+	+	EMS mutant	-
Propino	+	+	+	+	Quench*NFC Tipple [b]	Syngenta
Appaloosa	+	+	+	+	493113-502*Decanter	Nickerson-Advanta Seeds UK Ltd. (Limagrain)
Riviera	+	+	+	+	Stanza*Cebeco 8331	PBI Cambridge Ltd.
Tocada	+	+	+	+	Henni*Pasadena	KWS
Kenia	+	+	+	+	Binder*Gull	Abed Plant Breeding Stn., Denmark
Morex	+	+	+	+	Cree*Bonanza	Dept Agri, University Minnesota
Aramir	+	+	+	+	Volla*Emir	Cebeco, Netherlands
Bowman	+	+	+	+	((Klages*(Fergus*Nordic))*ND 1156)*Hector	North Dakota Agri Exp Stn
Troon	+	+	+	+	Extract*NSL 95-2949	Nickerson (UK) Ltd. (Limagrain)

Table 1. *Cont.*

Cultivar	Trials				Pedigree [a]/Note	Breeder
	2013	2014	2015	2016		
Vada	+	+	+	+	*H.laevigatum**Gull	Instituut de Haaff, Netherlands
Decanter	+	+	+	+	Heron*Dallas	Limagrain
Golden Promise	+	+	+	+	Maythorpe Gamma-Ray Mutant	Zenica
Carlsberg	+	+	+	+	Prentice*Maja	Carlsberg
NFC Tipple	+	+	+	+	(NFC 497-12*Cork)*Vortex	New Farm Crops Ltd. (Syngenta)
Melius	+	+	+	+	Conchita*TamTam	Syngenta
Prestige	+	+	+	-	(Bohemian Wheat*Rye)*(Ble de Domes*Garnet)	PBI Cambridge Ltd.
Carafe	+	+	+	-	(Linden*Cooper)*Extract	New Farm Crops Ltd. (Syngenta)
Scarlett	+	+	+	-	Amazona (Breun ST 2730e*Kym)	Bruen
Derkado	+	+	+	-	Lada*Salome	VEB Berlin
B83/12/21/5	+	+	+	-	Thurso*Esk	Scottish Crop Research Institute
RGT Planet	-	-	-	+	Concerto*TamTam	RAGT
KWS Sassy	-	-	-	+	Publican*Concerto	KWS
Olympus	-	-	-	+	Genie*Tesla	Limagrain
Octavia	-	-	-	+	Odyssey*SY Universal	Limagrain
Sienna	-	-	-	+	Chronicle*Genie	Limagrain
Odyssey	-	-	-	+	Concerto*Quench	Limagrain
Origin	-	-	-	+	NSL07-8113-B*Tesla	Limagrain
Fairing	-	-	-	+	144-02-4*Titouan	Syngenta
Belgravia	-	-	-	+	Minstrel*Westminster [b]	Limagrain
Ovation	-	-	-	+	Tesla*Odyssey	Limagrain
Scholar	-	-	-	+	Summit*SJ056065	Syngenta

[a] Pedigree information from John Innes Centre Germplasm Resources Unit (GRU) Searchable database for BBSRC Small Grain Cereal Collections (https://www.jic.ac.uk/germplasm/databases.htm) and barley pedigree data excel file apart from those marked. [b]: HGCA Recommended List Barley and Oats Pocketbook 2011/12; & 2014/15 [18]. [c] Root hair mutants induced by EMS. Note: the highlighted—last 11 cultivars replaced those likewise highlighted in 2016.

2.2. Trial Design

To determine robustness of any relationships between cultivars and tillage conditions identified, many of these were tested across three or four seasons. Four different soil tillage conditions were used, but primarily these compared inversion and non-inversion tillage for yield and disease. The soil tillage platform used was Mid Pilmore at the James Hutton Institute Mylnefield Farm (56°27′17.5″ N 3°04′55.3″ W or 56.454868, −3.082019), set up in 2003 [17] and it was previously used to show differential response of winter barley cultivars to tillage treatments (Newton, unpublished).

Five tillage treatments represented different levels of soil disturbance in a sandy-loam soil: (T1) zero tillage and (T2) minimum or shallow non-inversion tillage to 7 cm depth were the non-inversion treatments. The inversion or ploughed treatments followed by power harrowing consisting of (T3) conventional plough to 20 cm depth, (T4) plough to 20 cm followed by compaction by wheeling the entire plot with a Massey Ferguson 6270 tractor fitted with 16.9R-38 rear tyres (8.8 Mg total load, 2.9 Mg wheel load and 110 kPa contact pressure), and (T5) deep plough to 40 cm depth. All tillage treatments were carried out immediately prior to sowing and always followed barley. These treatments were selected to provide different physical constraints to root growth and water availability. Fifteen blocks of 33 × 33 m were marked out in an even grid, with five blocks in each of three north-south columns representing the three treatment replicates. Blocks were separated from each other by strips at least 3 m wide that were sown with grass seed after the first trial year was sown. Within each of the 15 blocks, half of the trial was winter sown (not reported here) and half spring sown with the 34 entries described above, and only barley was ever grown on this site during these trial years. Plots measured 1.55 m wide × 6.0 m long, reduced to 4.8 m harvested length by plot definition, and were sown at a sowing rate of 360 seed/m^2 with an eight-row Hege plot drill with five plots per bed. Nitrogen fertiliser (350 kg/ha of 22-4-14 (7.5 SO_3)) was applied as top dressing. Standard pre- and post-emergence herbicide treatments were applied, but no fungicide treatments were used. Straw was removed from all plots following harvest. The T1 zero tillage treatment was discontinued due to the accumulating weed problems that compromised comparisons and is not reported here. Details of the soil physical properties and further details of the tillage platform and its previous use have been published [17,19–21].

2.3. Assessments

Any disease that occurred above trace levels was scored on a 1–9 whole plant severity scale [22] at approximately two-weekly intervals after first observation. Scores were analysed both directly or as converted percentage infection values. Plots were harvested when ripe using a Wintersteiger plot combine and the grain was dried to constant moisture and weighed.

2.4. Statistical Analysis

For the years 2013–2015 the yield and disease levels were analysed using an over-year mixed model fitted using REML (restricted maximum likelihood). The residuals for each trait were checked to see if they followed a normal distribution and the trait was transformed if required to normalise the distribution. Year, cultivar, treatment and all interactions among these were treated as fixed effects (FIXED = year*treatment*cultivar) while the blocking structure was fitted as random effects (RANDOM = (year.block)/wholeplot/subplot where wholeplot represents the areas to which the tillage treatments were randomised and plot the plots to which the 34 entries were randomised. A test for heterogeneity of the residual variance across years was carried out but was not significant for either trait and so a common residual variance was fitted. The 2016 trial was analysed separately using ANOVA as the cultivars were changed (i.e., year was removed from the terms above). The rankings of the cultivars based on the means of the inversion and non-inversion treatments were calculated, and also the change in rankings between these.

2.5. Seasonal Weather Data

A long-term weather station was situated 580 m to the east of the centre of the trial site, thus providing local weather data for all four seasons presented to aid interpretation of results. The mean monthly rain and the maximum and minimum temperatures for the trial site are presented in Figures 1 and 2. In any given month the minimum temperature ranged up to 3.3 °C and the maximum up to 5.5 °C, both being in March/April and were generally very similar in all seasons. The monthly rainfall averages across the six-month growing seasons for 2013–2016 were 48, 71, 63 and 54 mm respectively, but their seasonal distributions varied.

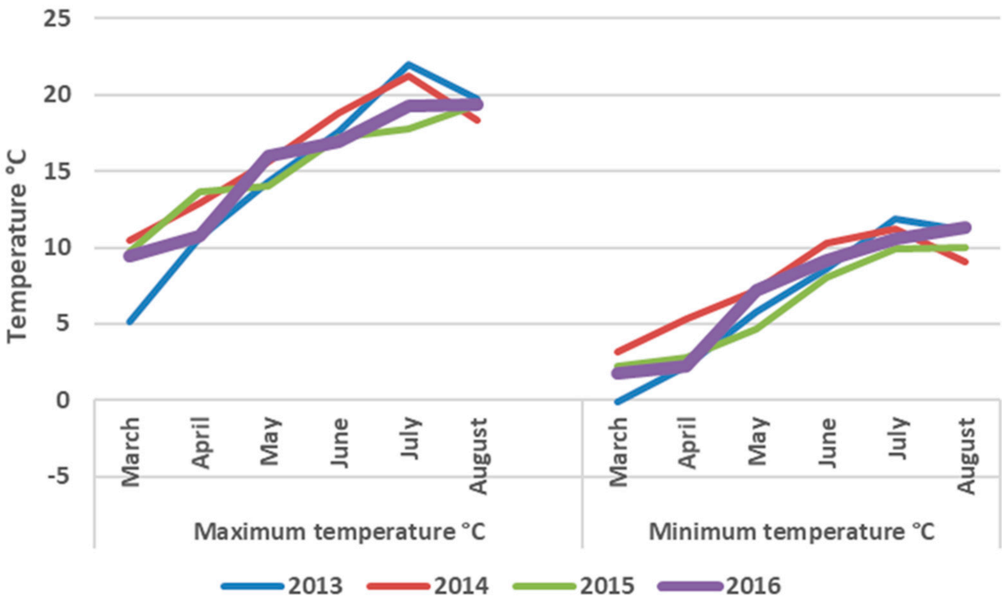

Figure 1. Maximum and minimum monthly mean temperatures for the four seasons of trials.

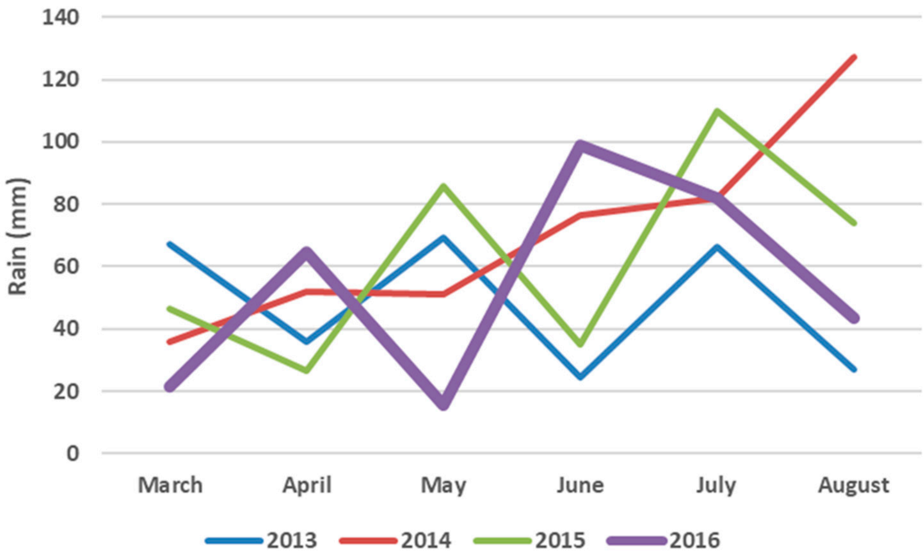

Figure 2. Monthly mean temperatures for the four seasons of trials.

2.6. Exploring Cultivar Ranking Changes

A simulation approach was used to explore how much cultivars can change in their rankings by chance. For each of the trial years 2013, 2014 and 2015, and separately for the 2016 trial, a split-plot ANOVA of the yield data was conducted, with the treatment model cvar*treat (cultivar-treatment interaction), then a second ANOVA, with treatment model cvar + treat (i.e., no interaction) was fitted. These gave fitted values that mimic the observed data in structure and blocking and which have the same means for the different levels of cultivar and tillage treatment, but no cvar*treatment interaction; hence any changes in cultivar rank within these treatments are assumed to be due to chance.

For each year, 200 random variables were constructed by forming 200 random permutations of the residuals for that year and adding these, in turn, to the fitted values for that year. The three sets of random variables were stacked to give 200 random variables: the simulated yields for the three years. Each simulated variable was analysed using REML for the three years together. The table of cultivar*treat means and levels were combined to give means for inversion and non-inversion. Then the difference in ranks between the inversion and non-inversion cultivars were calculated giving a distribution of the change in ranks that could occur by chance in data of a similar structure to the observed set.

3. Results

3.1. Disease

The only disease that occurred every year was rhynchosporium, also known as scald or barley leaf blotch, causal agent *Rhynchosporium commune*, but infection levels were never severe and were unlikely to directly impact yield. The number of scores made varied from year to year so the most appropriate comparison was made using the mean of the raw scores (Figure 3), converted to percentages. An angular transformation was found to be necessary to normalise the data. For the data from 2013–2015 the mean rhynchosporium scores were statistically significantly different ($p < 0.001$) for cultivar, and year*cultivar and there was some evidence of a year*treatment interaction ($p = 0.015$) but neither treatment*cultivar nor treatment*cultivar*year were statistically significant. The 2016 treatment effects followed a similar trend to the earlier trials.

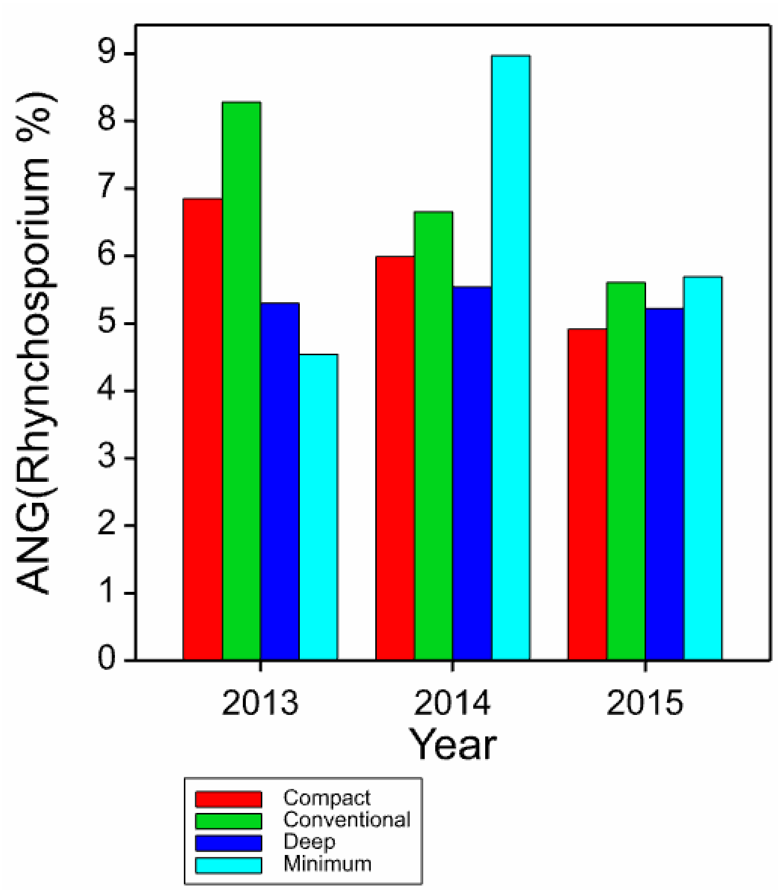

Figure 3. Significant interaction between cultivation treatment and year for rhynchosporium symptom score. An angular-transformed score of 5 = 0.8%, 6 = 1.1%, 7 = 1.5%, 8 = 1.9%, 9 = 2.4%. Compact, conventional and deep are inversion cultivation, minimum is non-inversion cultivation. Average SED (standard error of difference) = 1.237.

3.2. Yield

In the mixed model of the yield data from 2013–2015 the residuals followed a normal distribution so there was no need to transform the data. There were significant effects of year ($p = 0.004$), cultivation treatment ($p < 0.001$) and cultivar ($p < 0.001$). All two-way interactions were also all significant, (year*treatment, p = 0.011; year*cultivar, p < 0.001; treatment*cultivar, p < 0.001) though not the three-way interaction year*treatment*cultivar. The year*treatment interaction clearly shows the lower yield effect of the minimum tillage treatment and the overall difference between years (Figure 4).

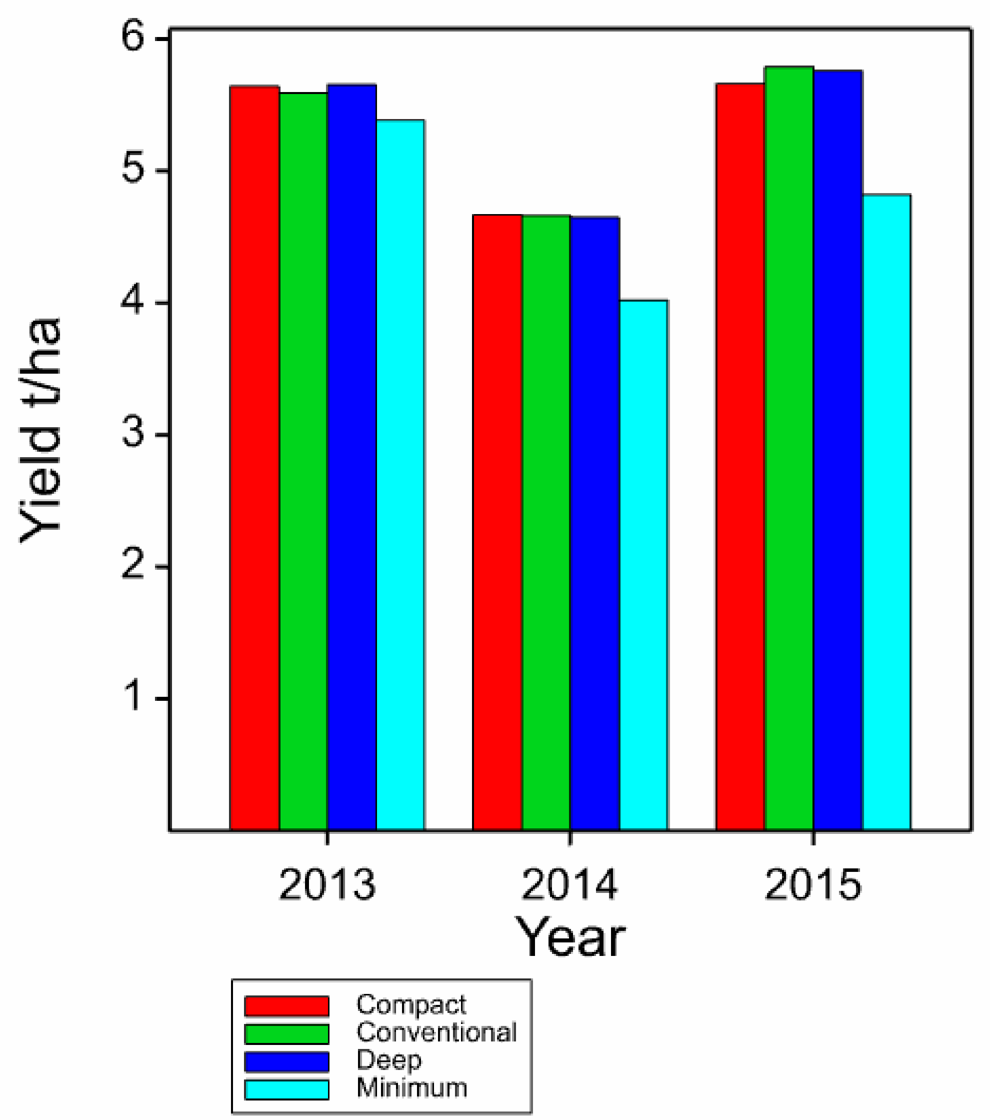

Figure 4. Mean yield response to soil cultivation treatment in each year. Compact, conventional and deep are inversion cultivation, minimum is non-inversion cultivation. Average SED = 0.209.

The yield differences ordered by the mean of the inversion tillage treatments show the marked similarity in performance between the three inversion tillage treatments, the contrasting yield performance of the non-inversion minimum tillage treatment and the variation in non-inversion tillage yield with respect to the inversion tillage yields (data not shown). In Table 2 cultivars are sorted in ascending order of the difference in yield ranking for inversion and non-inversion tillage. The inversion tillage mean (column 2) is calculated from the mean of the plough, conventional and compaction inversion treatments and the minimum tillage was used for the non-inversion treatment. The rank difference inversion minus non-inversion gives negative values where non-inversion yield ranks higher, i.e., inversion adapted, and positive where inversion tillage ranks higher i.e., non-inversion adapted. Both rankings and actual yield differences are presented as the latter are needed for effective interpretation, especially when differences are small.

Table 2. Ranking of 2013–2015 spring barley cultivars by the difference between their inversion and non-inversion yield ranking.

Cultivar	Yield Inv.	Yield Non-Inv.	Rank Inv.	Rank: Non-Inv.	Rank Diff.	Yield Diff. Percent
						Inversion-adapted
Troon	5.53	4.54	16	25	−9	17.98
Appaloosa	5.74	4.81	8	16	−8	16.14
T-short root hairs-R	5.25	4.41	23	28	−5	15.88
Morex	5.54	4.76	15	19	−4	14.03
V-short root hairs-R	4.88	4.28	28	32	−4	12.38
Wa/We	5.89	5.10	2	6	−4	13.51
Op/We	5.69	4.93	9	12	−3	13.35
Optic	5.35	4.54	21	24	−3	15.17
Propino	5.79	4.95	6	9	−3	14.53
We/Co	5.75	4.94	7	10	−3	14.01
Derkado	4.83	4.31	29	31	−2	10.76
Wa/Co	5.82	4.97	5	7	−2	14.57
Melius	5.84	5.25	3	4	−1	10.10
Op/Wa	5.50	4.78	17	18	−1	13.11
Scarlett	5.26	4.57	22	23	−1	13.06
Aramir	4.58	4.26	33	33	0	6.89
Bowman	3.79	3.83	34	34	0	−0.98
Carafe	5.09	4.50	26	26	0	11.56
Kennia	4.71	4.36	30	30	0	7.44
NFC Tipple	5.56	4.90	14	14	0	11.95
Tocada	5.58	4.92	13	13	0	11.88
Westminster	5.90	5.35	1	1	0	9.24
Op/We/Wa/Co	5.62	4.94	12	11	1	12.16
Prestige	5.24	4.64	24	22	2	11.47
Waggon	5.82	5.26	4	2	2	9.69
B83-12/21/5	5.50	4.82	18	15	3	12.41
Decanter	5.42	4.80	20	17	3	11.45
Golden Promise	4.58	4.39	32	29	3	4.17
Riviera	5.11	4.66	25	21	4	8.84
Vada	4.62	4.43	31	27	4	4.24
Q-no root hairs-S	5.64	5.15	11	5	6	8.69
Carlsberg	4.93	4.73	27	20	7	4.06
Concerto	5.65	5.25	10	3	7	7.14
Op/Co	5.44	4.95	19	8	11	8.94
						Non−inversion adapted

Cultivars and cultivar mixtures are ranked in order of yield, 1 being the highest-yielding. Column 6 is the rank difference between the mean of the plough, conventional and compaction inversion treatments and the minimum tillage non-inversion treatment. Cultivars are ordered by the rank difference inversion minus non-inversion, which has negative values where non-inversion yield ranks higher and positive where inversion tillage ranks higher. Shaded values highlight the most adapted cultivars. Bold highlights cultivar mixtures and their component monocultures (underlined).

The yield gap between the inversion and non-inversion tillage treatments tends to increase with inversion tillage yield (column 7 in Table 2 and Figure 5). The lowest-yielding cultivars tend to differ little in yield response between tillage treatments whereas the highest-yielding cultivars, such as Appaloosa and Troon, show relatively poor non-inversion tillage yield. The highest-yielding four commercial cultivars under non-inversion tillage were Westminster, Melius, Waggon and Propino, while Bowman, Aramir, Golden Promise and Vada were the lowest four for yield. Notable as only appearing in the top eight for non-inversion tillage were Concerto and the Optic/Concerto mixture, and similarly Appaloosa in the inversion tillage indicating differential adaptation to tillage. The other cultivars such as Troon and Carlsberg identified as potentially tillage treatment-adapted (Table 2) were not competitive on their yield, showing that there is no overall correlation of tillage adaptation with yield in general. This is further illustrated by Appaloosa which had the eighth highest yield in inversion tillage, but much lower in non-inversion tillage (16% yield reduction) and Troon follows a similar pattern (18% yield reduction) (Table 2). Conversely, Concerto improves its ranking from inversion to non-inversion tillage (7% yield reduction) and likewise Carlsberg and the Optic/Concerto mixture (4% and 9% yield reduction respectively).

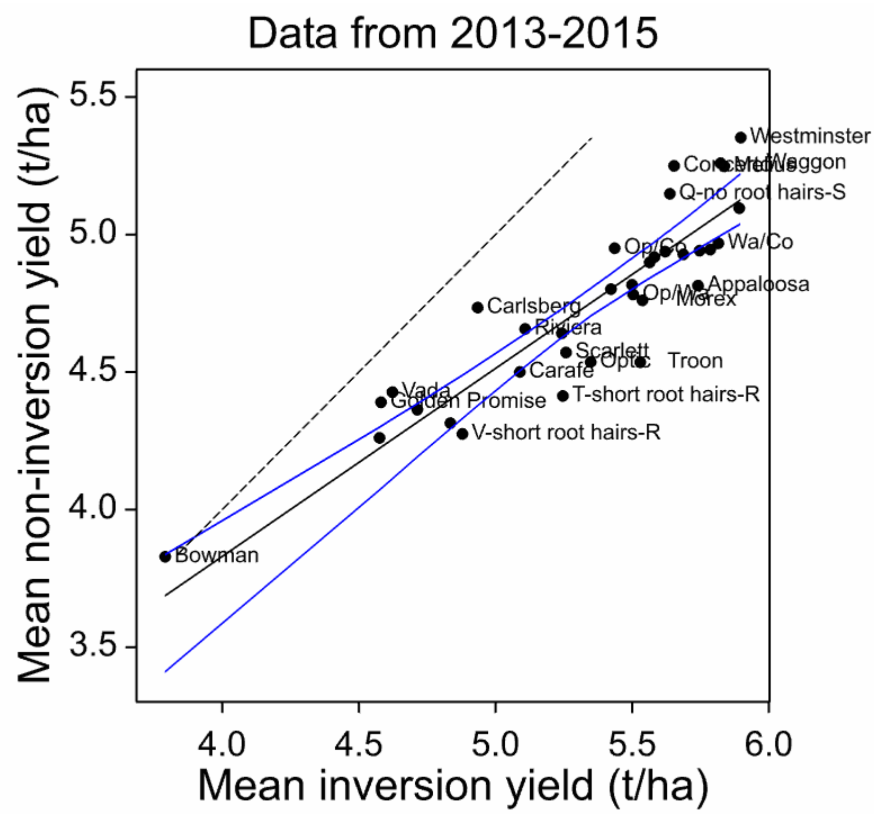

Figure 5. Regression of inversion yield on non-inversion yield for spring barley cultivars 2013–2015. The blue lines show the 95% confidence interval about the regression line (solid black) while the dashed line shows the 1:1 yield ratio. Only cultivars outside the confidence interval are named for clarity.

Bowman stands out as the lowest-yielding cultivar and that with the smallest percentage difference between inversion and non-inversion tillage yield. As a North American-bred cultivar of very different pedigree from all the other cultivars, this serves as a useful check, emphasising the relevance of the contrasting cultivation responses of the other cultivars. Regressing the non-inversion yield on the inversion yield (using functional regression as both measures of yield are affected by random variation) the non-inversion adaptation of Concerto and the lower-yielding Carlsberg are clear, and likewise Appaloosa and the lower-yielding Troon for inversion tillage adaptation (Figure 5).

Three of the two-component mixtures tend to reflect the performance of an individual component rather than the mean, spread from non-inversion- to inversion-adapted (Op/Co, Op/Wa and Op/We) (bold in Table 2). The other three (We/Co, Wa/Co and Wa/We) all rank more towards inversion adaptation, but represent no consistent difference from the mean of their component cultivars.

In the 2016 trial Appaloosa was again clearly the most inversion tillage adapted cultivar and Riviera, Tocada and Carlsberg were among the most non-inversion adapted (shaded text in Table 3; Figure 6). The latter were joined by a more recent cultivar (AHDB Recommended List (RL) listed 2016), Fairing, while the former was joined by another new cultivar, Scholar (RL listed 2015). Concerto changed designation and was now among the inversion adapted. However, as noted above these cultivars are not competitive in their yield overall and this designation is more a reflection of their particularly poor non-inversion yield. The remaining four-component mixture moved towards the inversion tillage adapted group, reflecting the trend in this direction found amongst some of the two-component mixtures. Other new cultivars were spread across the spectrum, mostly towards the inversion-adapted end, but KWS Sassy stands out as both high-yielding and more non-inversion adapted. Regressing the non-inversion yields with the inversion yield (Figure 6) the non-inversion adaptation of KWS Sassy and the lower-yielding Fairing, Riviera and Carlsberg are clear, and likewise Scholar, and Appaloosa for inversion tillage adaptation. However, the relative yield of the non-inversion tillage in 2016 was very low, Bowman was not such a low outlier, and the trend towards increasing yield and greater difference between inversion and non-inversion tillage was not as strong as in the 2014–2016 trials mean.

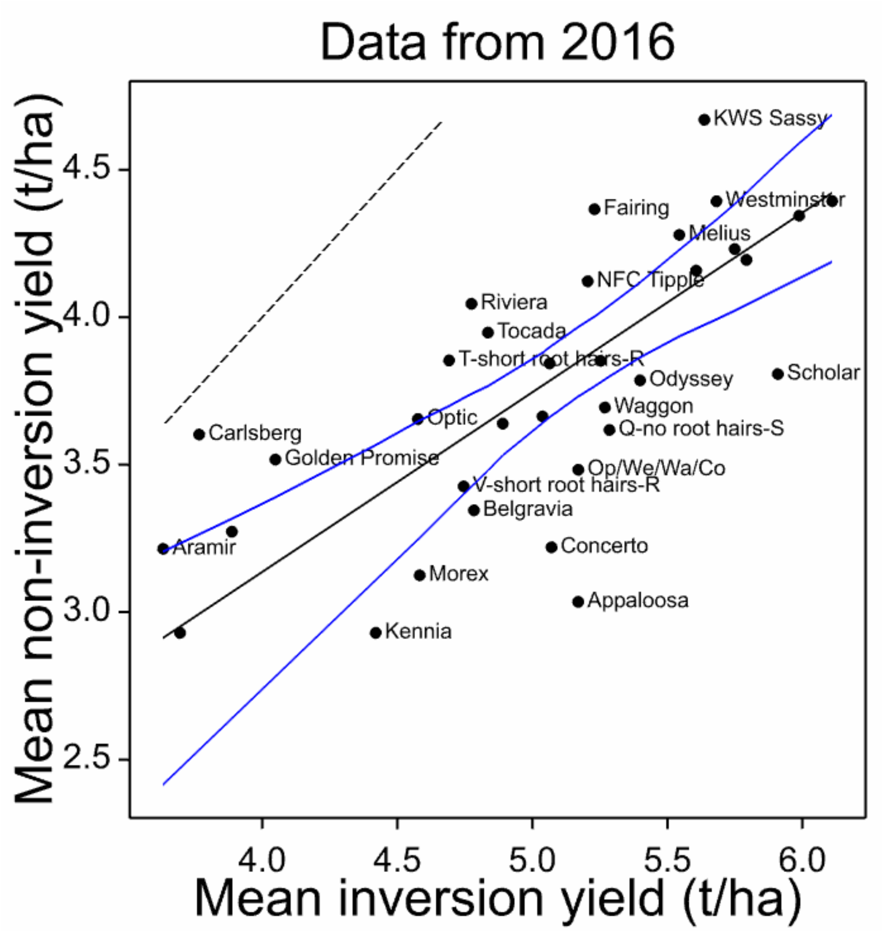

Figure 6. Regression of inversion yield on non-inversion yield for spring barley cultivars 2016. The blue lines show the 95% confidence interval about the regression line (solid black) while the dashed line shows the 1:1 yield ratio. Only cultivars outside the confidence interval are named for clarity.

Table 3. Ranking of 2016 trial spring barley cultivars by the difference between their inversion and non-inversion yield ranking.

Cultivar	Yield Inv.	Yield Non-Inv.	Rank Inv.	Rank: Non-Inv.	Rank Diff. Percent	Yield Diff.
						Inversion-adapted
Appaloosa	5.17	3.03	17	32	−15	41.30
Scholar	5.91	3.81	3	16	−13	35.57
Concerto	5.07	3.22	18	29	−11	36.50
Q-no root hairs-S	5.29	3.62	11	22	−11	31.55
Op/We/Wa/Co	5.17	3.48	16	25	−9	32.64
Odyssey	5.40	3.79	10	17	−7	29.88
Waggon	5.27	3.69	12	18	−6	29.89
Belgravia	4.78	3.35	23	27	−4	30.07
Kennia	4.42	2.93	29	33	−4	33.71
Morex	4.58	3.12	27	31	−4	31.81
Olympus	5.79	4.19	4	8	−4	27.59
Sienna	5.99	4.34	2	5	−3	27.45
Origin	5.75	4.23	5	7	−2	26.40
RGT Planet	6.11	4.39	1	2.5	−1.5	28.10
Bowman	3.70	2.93	33	34	−1	20.72
Octavia	5.25	3.85	13	14	−1	26.66
Propino	5.61	4.16	8	9	−1	25.84
V-short rt hrs-R	4.75	3.43	25	26	−1	27.80
Decanter	4.89	3.64	21	21	0	25.59
Troon	5.04	3.66	20	19	1	27.28
Melius	5.54	4.28	9	6	3	22.82
Vada	3.89	3.27	31	28	3	15.81
Westminster	5.68	4.39	6	2.5	3.5	22.68
Aramir	3.63	3.21	34	30	4	11.52
Ovation	5.06	3.84	19	15	4	24.10
NFC Tipple	5.20	4.12	15	10	5	20.81
Golden Promise	4.05	3.52	30	24	6	13.12
KWS Sassy	5.64	4.67	7	1	6	17.16
Optic	4.58	3.65	28	20	8	20.14
Carlsberg	3.77	3.60	32	23	9	4.35
Fairing	5.23	4.37	14	4	10	16.52
Tocada	4.84	3.95	22	12	10	18.36
Riviera	4.77	4.05	24	11	13	15.27
T-short rt hrs-R	4.69	3.85	26	13	13	17.87
						Non-inversion adapted

Cultivars are ranked in order of yield, 1 being the highest-yielding. Column 6 is the rank difference between the mean of the plough, conventional and compaction inversion treatments and the minimum tillage non-inversion treatment. Cultivars are ordered by the rank difference inversion minus non-inversion, which has negative values where non-inversion yield ranks higher and positive where inversion tillage ranks higher. Shaded text highlights most adapted cultivars. New cultivars in the 2016 trial are bold underlined.

Focusing on the yield, in this trial several of the eleven new cultivars included showed high non-inversion tillage yield, notably KWS Sassy, RGT Planet, Fairing, Sienna, Origin and Olympus, and an older cultivar, Westminster (Table 3). The high inversion tillage yield list is similar except that it includes Scholar as well, but its non-inversion tillage yield is 36% less, dropping from 3 to 16 in the cultivar rankings. In contrast, Fairing and KWS Sassy only lose 17% of their yield in non-inversion tillage, changing from 14 to 4 and 7 to 1 in the rankings. However, these data are from a single site in just one year and showed particularly poor non-inversion tillage yields overall, which may explain the change in apparent adaptation of Concerto and therefore the 2016 data in particular need further validation.

The lowest-yielding cultivars were Aramir, Bowman, Vada, Kennia and Morex (Table 3 and Figure 6). Notable as only appearing in the top eight for non-inversion tillage was Fairing, and Scholar in the inversion tillage suggesting differential adaptation to tillage. As with the 2013–2015 trials, other cultivars such as Optic, Carlsberg and Appaloosa again were identified as potentially tillage treatment-adapted were not competitive on their yield, but Concerto, Golden Promise and Belgravia could be added to this list too.

Amongst the Optic root hair mutants, the two short root hair mutants showed inversion adaptation in the 2013–2015 trials, as does their parent Optic to a lesser extent. In contrast the no root hair mutant ranks in the non-inversion adapted cultivars. However, this pattern is not upheld in the 2016 data but as root hair differences are likely to show enhanced responsiveness to soil environmental stresses, particularly water availability, the three year mean data will even out this variability and is therefore more likely to be robust.

3.3. Cultivar Ranking Changes

The simulation study looked at the changes in rank that can occur by chance in a data set of this structure. Table 4 summarises this for the 2013–2015 experiments, using the absolute changes in rank. For example, consider a change in absolute rank of six or more. In the experimental data six cultivars changed rank by six or more positions. In the 200 simulations two simulations had no cultivars that changed rank by six or more, while one simulation had 10 cultivars that changed rank by six or more. The median number of cultivars that changed rank by six or more was four. The 90% point was six cultivars and the 95% point was seven cultivars. Table 5 shows the corresponding information for the 2016 trial. For the trials in 2013–2015 the observed rank changes are close to the upper 90% point of the changes that were observed by chance in the simulated data, but for 2016 the observed changes exceed the 95% point of the simulation distribution.

Table 4. Absolute rank differences for combined 2013–2015 trials. No. cultivars shows the number of cultivars with the given rank change and Cumulative shows the number with that rank change or greater. The 50%, 90% and 95% points are from the simulated distribution of the number of cultivars that exhibited an absolute rank change at least as large as that specified, as described in the text.

Rank Change	No. Cultivars	Cumulative	50%	90%	95%
0	7	34	34	34	34
1	4	27	28	30	31
2	4	23	19	23	24
3	7	19	13	17	18
4	5	12	9	12	13
5	1	7	6	9	10
6	1	6	4	6	7
7	2	5	2	4	5
8	1	3	1	3	4
9	1	2	1	2	3
11	1	1	0	1	1

Table 5. Absolute rank differences for 2016 trial. No. cultivars shows the number of cultivars with the given rank change and Cumulative shows the number with that rank change or greater. Rank changes have been rounded up to the nearest integer. The 50%, 90% and 95% points are from the simulated distribution of the number of cultivars that exhibited an absolute rank change at least as large as that specified, as described in the text.

Rank Change	No. Cultivars	Cumulative	50%	90%	95%
0	1	34	34	34	34
1	5	33	29	32	32
2	2	28	21	25	25
3	3	26	15	19	20
4	6	23	11	15	16
5	2	17	8	11	12
6	3	15	5	8	9
7	1	12	3	6	7
8	1	11	2	4	5
9	2	10	1	3	4
10	2	8	1	2	3
11	2	6	0	1	2
13	3	4	0	1	1
15	1	1	0	0	0

The simulation showed that there were five trial entries that have a rank change of seven or more for the 2013–2015 trials, which had a probability of less than 10% of occurring by chance in the simulation study (Table 4). The changes were positive (i.e., non-inversion adapted) for Op/Co, Concerto and Carlsberg, and negative for Troon and Appaloosa. For the 2016 trial there were 11 cultivars that had a rank change of eight or more (Table 5). These were positive for T-short root hairs-R, Riviera, Tocada, Fairling, Carlsberg and Optic; negative for Appaloosa, Scholar, Concerto, Q-no root hairs-S, Op/We/Wa/Co.

4. Discussion

While most cultivars of spring barley in these trials performed similarly, relative to trial means under all tillage conditions, a few did not. The variance from their expected yield was related to whether tillage was inversion or non-inversion. In these experiments and previous work [16] there was no difference between just the three inversion tillage treatments with respect to cultivar yield and therefore no differences such as compaction could be related to cultivar yield. Although only one non-inversion tillage treatment was used in this work, previously zero and minimum tillage treatments had performed similarly and both had been very different from the inversion tillage treatments.

For disease, namely rhynchosporium, there was a trend to increased disease in non-inversion tillage treatments previously [23] and this was also found here, though levels were low. However, no overall tillage by cultivar interactions were found. Whereas the three inversion tillage treatments gave very similar rhynchosporium levels in all four years, in 2014 and 2016 the non-inversion tillage gave more symptoms whereas in 2013 and 2015 they remained similar to the inversion tillage levels. This is likely to be explained by more inoculum being available for infection in the crop residue in the non-inversion tillage and favorable epidemiological conditions occurring early season when this factor has more impact [24]. In particular, rainfall in April has been suggested as particularly important for splashing inoculum onto the foliage [24] and unpublished data), and this was highest in 2014 and 2016 (Figure 2). Although straw was removed from the site post-harvest, sufficient infected stubble remains in the non-inversion treatment to provide inoculum, whereas in inversion tillage it is buried.

In the 2013, 2014 and 2015 trials the lowest-yielding cultivars also tended to have a smaller difference between inversion and non-inversion tillage yield, shown most clearly in the lowest-yielding cultivar, Bowman. The highest-yielding cultivars under non-inversion tillage tended to have the greatest yield under inversion tillage as well, but the yield difference between inversion and non-inversion was not correlated with cultivar yield overall. Amongst the middle-ranking cultivars there were some contrasting yield trends with respect to tillage treatment interactions. Both Appaloosa and Troon showed large yield differences comparing inversion tillage with non-inversion tillage (~19%), but Concerto and Carlsberg had only small yield penalties (3%–6%) under non-inversion tillage. In 2016, the non-inversion tillage treatment showed greatly reduced yield overall but amongst the 11 new cultivars trialed in 2016 both KWS Sassy and Fairing had relatively small reductions. The new cultivar KWS Sassy was also the highest-yielding cultivar under non-inversion tillage, whereas Fairing was fourth and lower ranking still under inversion tillage (14th). However, the two highest-yielding cultivars under inversion tillage, RGT Planet and Sienna, both showed a substantial yield reduction under non-inversion tillage. This was far less than the third largest-yielding cultivar under inversion tillage, Scholar, which showed a 36% reduction in yield under non-inversion tillage, although these data are from a single trial and therefore preliminary. These data demonstrate that there is significant variation in cultivar adaptation to non-inversion tillage and lends weight to the argument that cereal cultivars should be bred and recommended specifically for this agronomic practice.

The two short root hair mutants were similarly adapted in the 2013–2015 trials, as was their parental normal length root hair cultivar Optic, towards the inversion tillage adapted end of the distribution. In contrast, the no root hair mutant was higher-yielding under inversion tillage, but with an even greater yield increase under non-inversion tillage ranking it is clearly close to the top of the non-inversion tillage end of the distribution. In the 2016 trial these relationships were different so caution should be taken in interpreting these data. However, 2016 showed the most contrasting rainfall distribution pattern of the four trial years, particularly in mid-season, being the lowest in May and highest in June (Figure 2) affecting water availability and crop water stress status. Nevertheless, previous findings would indicate that these relationships with root hairs found in the 2013–2015 trial means would be expected. In non-inversion tillage soils the soil density will be greater and there is likely to be greater root-soil contact as observed [14]. Under such circumstances the value of root hairs for maintaining root-soil contact and helping access water and nutrients such as phosphorus will be less [14,15]. In looser soil as seen in inversion tillage systems, soil/root contact will be enhanced by root hairs. That the hairless-mutant gave more yield under both conditions is not explained by these observations. Nevertheless, root system architectural traits, such as root hair production, may be useful traits to select for to differentiate cultivars for the different production systems.

Testing the rank changes by simulating how many could occur by chance indicated that the changes observed in 2013–2015 were at the high end of the simulated distribution (around the 90% level) and those observed in 2016 were above the 95% level. Ranking change is dependent on both the number of entries in the trial, the absolute yield differences in each year, and the range represented by the entries chosen. Furthermore, year-to-year differential responses of each cultivar are compounded by analysing the three trials together. Therefore, it is difficult to interpret the practical significance of these differences. Nevertheless, these results do indicate that some cultivars are differentially adapted to cultivation treatments.

A caveat to all these cultivar adaptation trends is that the site was sown with barley continuously, so soil microbial populations may be skewed but this is offset by any effects of previous cropping differences being minimised. Furthermore, continuous spring barley growing by farmers in the region is not uncommon. However, any single crop species grown continuously will have effects on the soil structure that ideally should be improved by the inclusion of other crops in a rotation or cover crops. The weather each season might also skew adaptation trends but the mean monthly weather data showed each season overall to be within the normal variance expected. However, notable was the contrasting rainfall pattern of 2016 in particular, whilst 2013 and 2015 were perhaps most similar (Figure 1). We have also focused on soil tillage and as soil type*cultivar interactions can occur, these could be compounded with soil tillage interactions too, but within a sandy loam soil type these comparisons are useful.

Clearly, the yield gains in some recent cultivars shown in RL trials may not be always realised under non-inversion tillage. It could be argued that our non-inversion tillage treatment may equate to, or serve as a proxy for, sub-optimal agronomy for some on-farm conditions. If the inversion tillage equates to the sort of official national or Recommended List trial high input, optimum conditions, then these data provide evidence that choice of cultivars should consider also the level of inputs and agronomic treatments, at least for soil tillage.

It was observed previously that soil tillage treatment differences have most impact on yield in years of environmental stress, particularly drought, and it is under such conditions that cultivar differences are most likely to be expressed. None of the trials reported here were subject to strong stress conditions, but by identifying cultivation interactions that are expressed across seasons it was still possible to identify cultivars with potentially robust differential responses to tillage treatments. Although cultivars more suitable to non-inversion tillage were identified, the transient commercial life of cultivars means that by the time these trials have been completed these data may be of limited on-farm application. It will be more valuable to use these differential response cultivars to identify the traits responsible for tillage adaptation, as breeding material for future cultivars, and for mechanistic studies where a few contrasting cultivars can be fully characterised during their growth. Previous work suggested that rooting structure physical traits are some of the most likely candidates for future breeding targets (Newton and Bengough, unpublished data).

5. Conclusions

Adaptation of cultivars of spring barley to either inversion tillage or non-inversion tillage was identified across years. Low-yielding old cultivars generally showed little adaptation and most elite cultivars yielded more under inversion tillage conditions. A few elite cultivars showed differential adaptation as indicated by a change in their relative ranking under the different tillage treatments. However, few very high-yielding elite cultivars were non-inversion tillage adapted, but they were strongly inversion tillage adapted. It is argued that the widespread use of non-inversion tillage on-farm means that inversion tillage yield data from the National List and other cultivar trials may not always identify the most appropriate cultivar for on-farm use.

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